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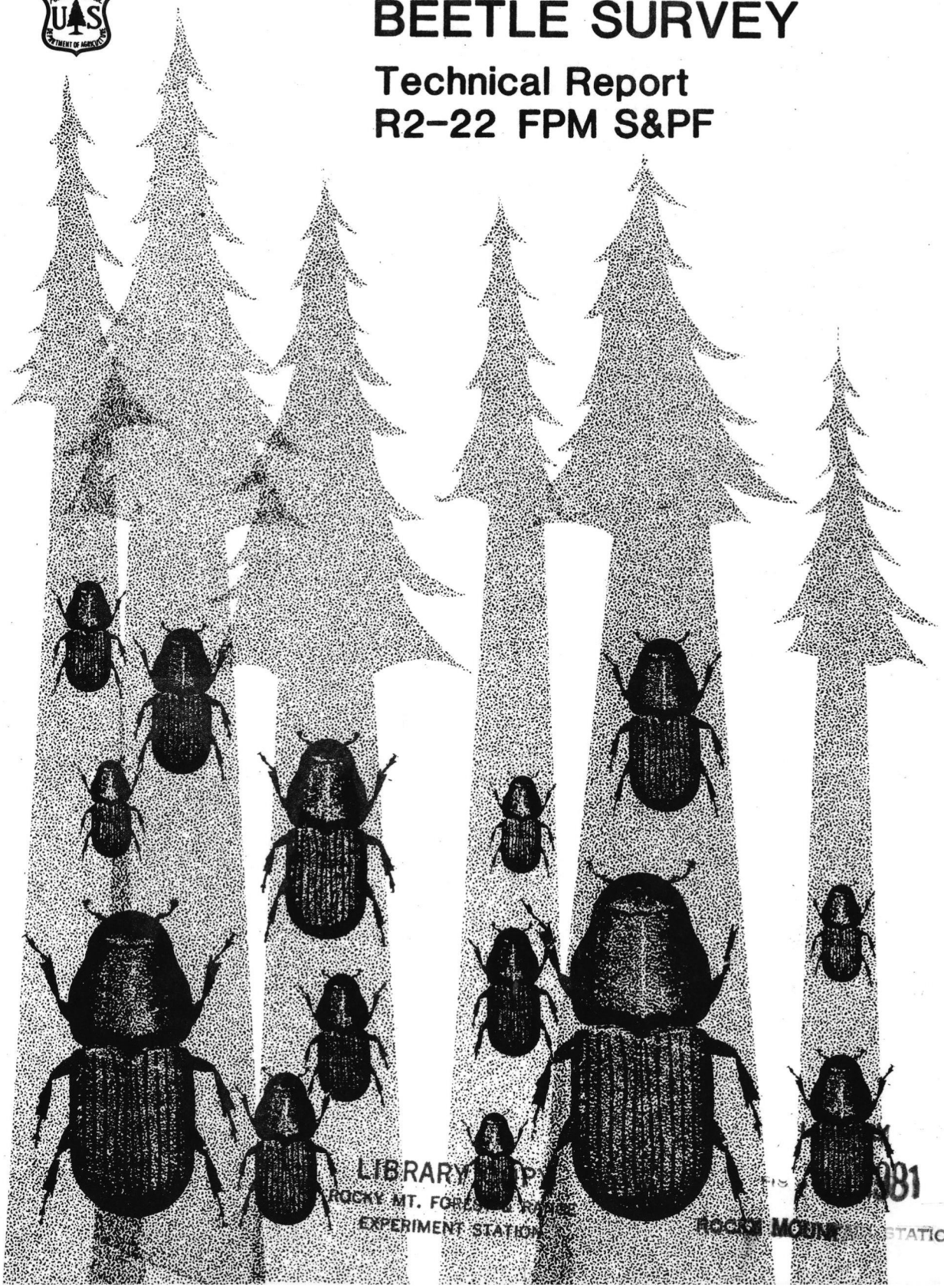
1979 COLORADO FRONT RANGE MOUNTAIN PINE BEETLE SURVEY

Technical Report R2-22 FPM S&PF



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1979 COLORADO FRONT RANGE

MOUNTAIN PINE BEETLE LOSS SURVEY

by

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ABSTRACT

A multistage survey to estimate tree mortality and volume on a statewide basis for Colorado was conducted in 1979. The survey methods are outlined in this report. The estimated number of faders (1978 attacked trees) was 327,443 trees from an infested area of 350,279 acres with an associated volume of 5.1 million cubic feet. Fader estimates and volumes pro-rated by ownership class are displayed for Colorado 1979 in the following table.

		Outbreak Area (M acres)	Number of trees (M trees)	Mortality (MMCF)
Colorado	National Forest	177.5	163.5	2.6
	Other Federal	7.0	6.9	0.1
	State, County or Municipal	7.7	7.3	0.1
	Nonindustrial Private	158.1	149.8	2.3
	Total	350.3	327.5+15%	5.1

Utilizing the estimate of 1979 faders (327,443) and the new mountain pine beetle infestation ratio (0.28) the estimated number of 1980 faders (1979 attacks) tree loss, was estimated to be about 92,000 ponderosa pine trees.

INTRODUCTION

In the western United States, bark beetles cause more tree mortality than any other insect group or any disease. In Colorado the "Front Range" outbreak of mountain pine beetle (MPB), *Dendroctonus ponderosae* Hopkins, has been highly visible and of public concern since 1972. Total tree loss from 1972 through 1978 is estimated to be 6.5 million.

To date, estimates of annual tree mortality and infestation acreages have been developed from aerial sketch mapping and ground observations. The accuracy or reliability of the estimates has seldom been challenged by the public, but has to some extent, by politicians, foresters and entomologists. Statistically reliable sampling procedures were not utilized.

Loss data that is sound and comparable is needed at the National or Regional level for major insects and diseases. These data provide a basis for projecting resource yields, essential for planning required in the National Forest Management Act (NFMA) and Resource Planning Act (RPA). Forest Pest Management has developed a data management system, Forest Insect and Disease Information System (FIDIS) to satisfy data needs for the planning processes.

Survey results in 1977 and 1978 from the Black Hills National Forest in Wyoming and South Dakota (Hostetler and Young 1979) and 1977 from the Targhee National Forest in Idaho (Klein et al) indicated reliable estimates of tree mortality can be obtained utilizing existing technology. Therefore, a statewide multi-stage survey of epidemic bark beetle infestations in the ponderosa pine of Colorado was conducted. MPB infestations in lodgepole pine in Colorado were not severe enough to include in the multi-stage survey.

Tree mortality estimates developed during this survey were reported by ownership and reported under the Forest Insect and Disease Information System (FIDIS) format.

OBJECTIVE

The objective of the 1979 survey was to estimate tree mortality and volume loss in ponderosa pine, *Pinus ponderosa*, Laws., due to the mountain pine beetle, *Dendroctonus ponderosae* Hopkins, in Colorado. Acres infested, trees killed and volume loss was reported by the required FIDIS ownership classes for the entire State.

The survey provided the following information:

1. The number, diameter distribution, and volume of ponderosa pine infested by MPB in 1978 (1979 faders).

2. The number, diameter distribution, and volume of merchantable dead (for firewood, etc.), standing and down ponderosa pine remaining in the area.

METHODS

Survey Area

Survey area was the "Front Range" of Colorado. The "Front Range" includes the Rocky Mountains east of the continental divide from the Wyoming state line on the north to the New Mexico state line on the south. The area contains over 4 million acres within the Montane zone, the first forested belt above the plains from 6,500 to 9,400 feet elevation.

The Montane zone includes grassland parks, stringer meadows, willow bottoms, brushy south-facing slopes, Douglas-fir on north-facing slopes, blue spruce along streams, open stands of trees with a herbaceous understory, and extremely dense stands of ponderosa and lodgepole pine with little more than a mat of needles and twigs on the ground. At lower elevations ponderosa pine blends into pinyon-juniper, shrublands, or grasslands. At higher elevations pine stands pure and mixed with aspen blend into spruce-fir.

The Front Range landownership pattern is extremely complex. There are thousands of small, privately-owned parcels, intermingled with public lands acquired through the Homestead Act and mining claim patents. Cities and counties have acquired lands primarily for recreation and municipal watershed purposes. The state owns scattered parcels throughout the area. U.S. Army, Air Force, and Bureau of Land Management administer small portions of the Front Range. About half of Rocky Mountain National Park is on the Front Range. National Forests comprise a large share of the whole area. The National Forests in the survey area are the Arapaho, Roosevelt, Pike and San Isabel. See Figure 1 for reference.

Survey Design

The initial plan called for a stratified two stage sampling design (Fig. 2). First stage sampling was based on photo plots selected systematically from two strata. Second stage samples were selected with probabilities

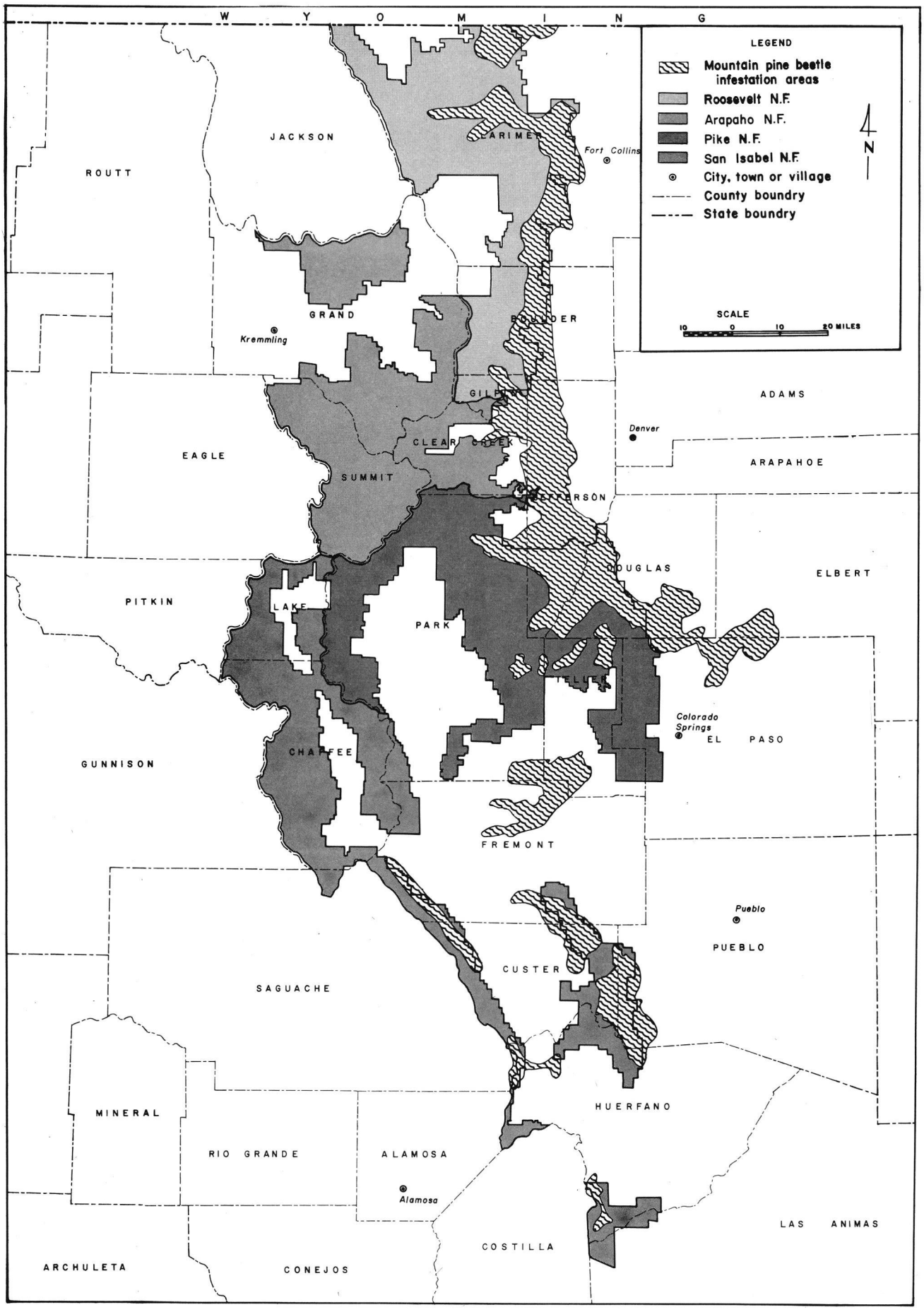

Figure 1.—Mountain pine beetle infestation areas surveyed in Colorado, 1979.

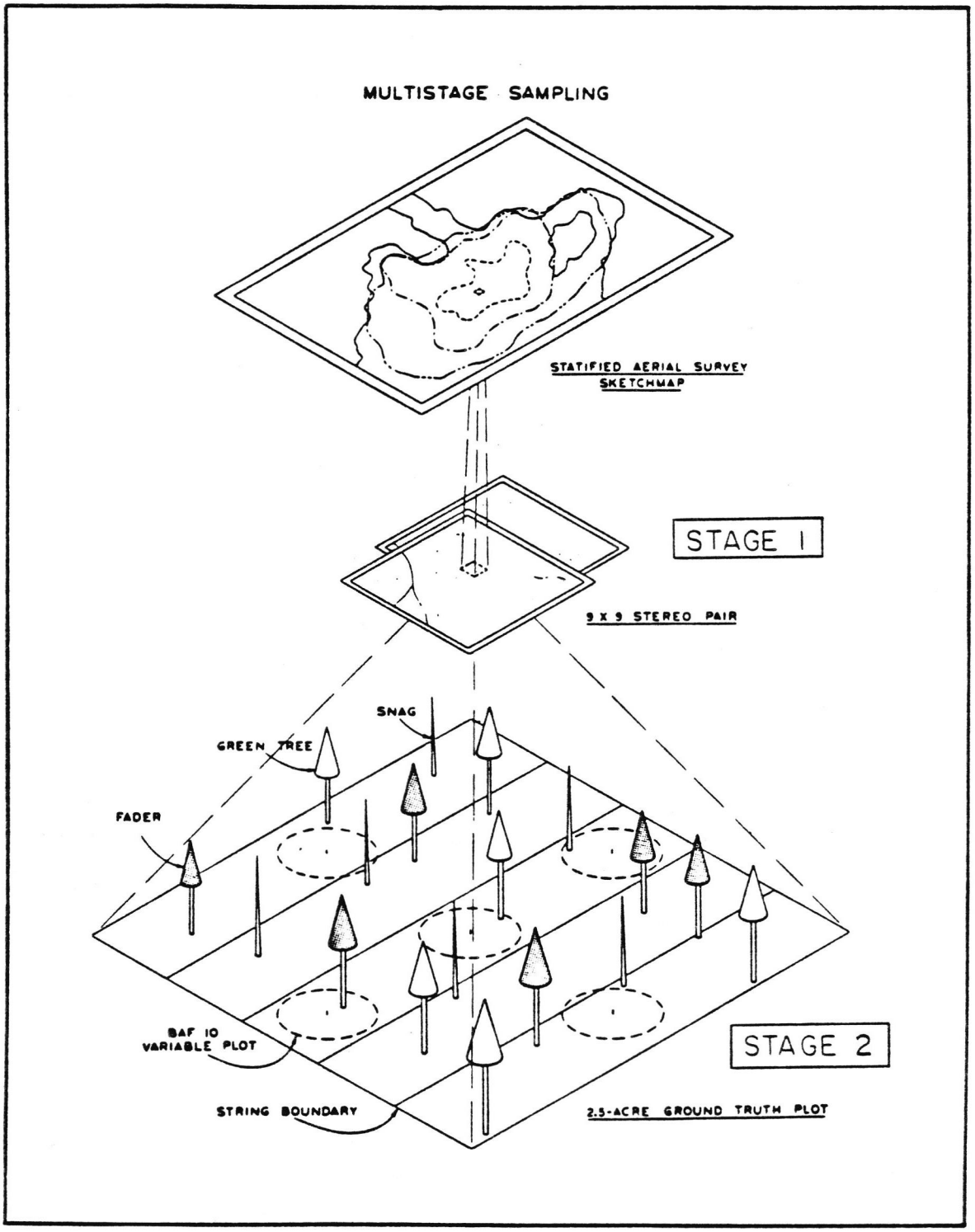

Figure 2. Diagrammatic representation of the stages and procedures used for the 1979 ponderosa pine mortality survey, Front Range of Colorado. (Modified and taken from Klein et al. (1979,p.5))

proportional to the number of 1979 faders (1978 MPB attacked) counted on the photo plots (Cochran 1977, p. 251). Subplots for ground sampling were selected, again by probabilities proportional to size (pps), from the selected photo samples. Fader numbers and volume estimates were determined on the ground. Other ground information was basal area of live to dead, new infestation ratios and an inventory of dead pine killed previously by MPB.

Specific details for each phase are discussed in the following section.

Aerial Sketch Mapping

On July 2, 1979 when most of the 1978 attacked trees were obviously discolored (fading) routine aerial sketch mapping procedures were initiated. The infestation areas were delineated by observers in a high wing light aircraft about 1500 feet above the terrain. Polygons of infested areas were delineated utilizing recognizable terrain features. A rough estimate of the number of fader trees within each of the polygons were recorded on topographic maps 1:24,000 (scale).

Stratification

Infestation boundaries with associated estimates of faders were transferred from the sketchmap to 1:126,720 scale (1/2 inch = 1 mile) planimetric BLM quads. Plastic (mylar) overlays were prepared for each quad. Acreages were then computed from each infestation area (polygon) using an electronic planimeter.

Infestations were segregated into two distinct strata, (1) contiguous, and (2) small and scattered. The contiguous strata consisted of many polygons adjoining each other making up a larger infestation area. A second strata was developed to incorporate many smaller polygons not common to each other (Fig. 3). Stratum boundaries were established for sampling purposes and have no biological significance. Sampling of the infestations was then conducted of a 350,279 acre infestation.

Sample Selection for Photo Mission

The contiguous strata included 320,229 acres from which a possible 3,558 primary sampling units (photo plots) existed. Employing a systematic selection procedure (Klein, 1979) 175 units were selected for photographic coverage. This achieved a sampling fraction of 5 percent (Table 1).

In the small and scattered strata, the primary sampling unit was the small infestation boundary (polygon). A probability proportional to size (pps) selection based on estimated faders was used to select 75 samples

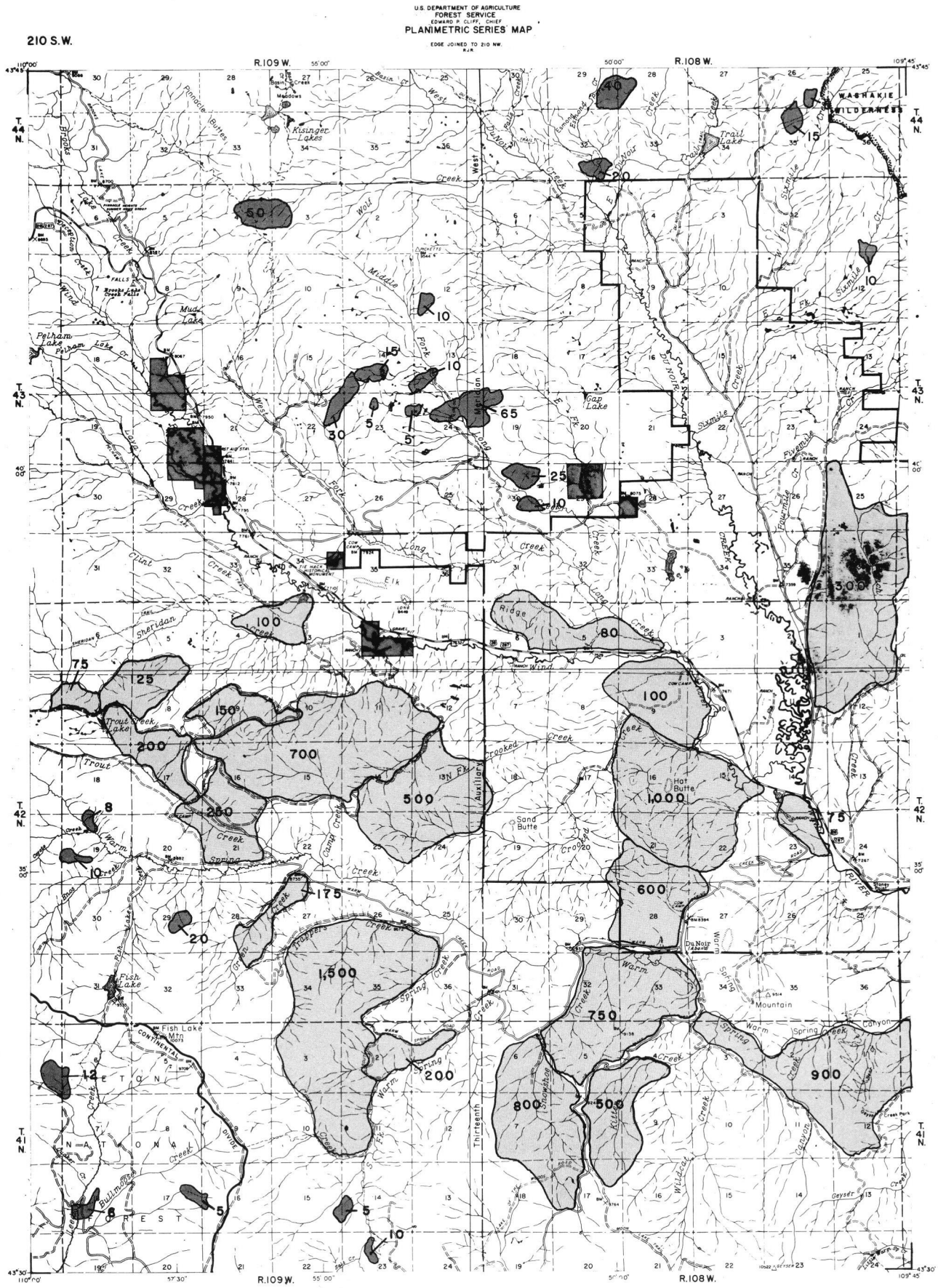

Figure 3. Example of survey area depicting Contiguous Strata (C) and Small & Scattered Strata (SS).

(polygons) from 593 polygons (Table 1). The small and scattered strata contained 30,050 acres. Useable photo plots were attained for 52 out of 75 polygons selected.

TABLE 1. 1979 Front Range Colorado Mountain Pine Beetle Loss Survey

Strata	Size of Strata (Acres)	Size of Photo Plot (Acres)	Number of Possible Plots	Photo Sample Size (Acres)	Ground Sample Size (No. Photo Plots)	Sampling Fraction
Contiguous	320,229	90	3,558	175	28	.049
Small and Scattered	30,050	Variable	593	52	20	-

The plot photography was taken during July 16 through August 7, 1979 using a Fairchild KA-2 (12 inch focal length) camera mounted in a T-337 aircraft. Color aerial film (MS-2448 and SO-397) 9x9 inch stereo triplets were taken of the 250 plots at a scale of approximately 1:6,000.

Photo Interpretation

A series of acetate templates were prepared for a range of scales (1:3,960 - 1:7,920). Etched on each acetate template were boundaries of a square 90-acre plot and a grid within delineating 36 square 2.5-acre subplots. The approximate scale for each photo plot was computed and the appropriate scale grid was overlayed to delineate the effective area of the plot. Photo plots were interpreted using Old Deft or equivalent stereoscopes. Interpreters recorded the number of visible faders within each subplot. In the contiguous strata there were 36 subplots of 2.5-acres for each photo plot. For the small and scattered strata the polygon boundaries were delineated on each plot photo and the proper template placed on the photo center. The number, shape and size of the subplots were limited as dictated by the polygon boundary when it was within the 90-acre grided template, some were 90-acre (36 subplots of 2.5-acres) as in the contiguous strata.

Ground Data Acquisition Sample Selection

A pps sampling scheme was used for each strata. From the contiguous strata, 30 photo plots were drawn based on photo interpretation counts, 28 of these were surveyed. From each selected 90-acre photo, two 2.5-acre subplots were then selected pps to be surveyed on the ground. The sampling scheme for the small and scattered strata was similar. Twenty photo plots were selected from which one 2.5-acre subplot was drawn.

Subplot boundaries were then etched on the emulsion side of the plot photo. Photo transparencies along with 1:24,000 U.S. Geological Survey topographic maps and 1:26,720 planimetric maps were used in the field to locate subplot boundaries. The transparencies were placed into light-weight film holders and examined with a pocket stereoscope using transmitted sunlight as the light source.

Ground data from the subplots were obtained using a crew of 2-3 people. The subplot boundaries were marked with string. Strips one-chain wide within each subplot were also bounded with string to expedite collection and accuracy of the data. The numbers of faders, dead trees (down and standing) and 1979-attacked ponderosa pines 5 inches DBH and larger were recorded by 1-inch diameter class. Height of three ponderosa pine for each 1-inch diameter class were measured for volume computation purposes.

Five variable plots were established in each subplot. One variable plot was located at the center of the subplot and one in each cardinal direction at 2 chains. A glass prism or Spiegal-Relascop (BAF 10) was used to determine tally trees. For borderline trees, one for each two were tallied. Trees 5-inches DBH and greater were recorded by 1-inch class of all live trees by species. Ponderosa was appropriately recorded as infested (attacked 1979), faders and dead. The horizontal length of one side boundary was measured for acreage determination at each subplot. For those subplots where slope was greater than 20 percent the horizontal length of two sides was measured and averaged. Actual acreage of each subplot was calculated and used in the number and volume estimates.

Statistical Analysis

Multi-stage estimation derived from previous surveys (Hostetler and Young 1978) were used for estimating the number of faders and volume lost in the contiguous stratum. Separate estimates were derived for the small and scattered stratum used in this year's survey. Specific formulae used for both stratum appear in Appendix A. The analysis consisted of (1) generating the number and volume of ponderosa pine killed, (2) determining the relationship between photo interpreter counts of faders and counts of faders on the ground, and (3) ratio of new infested trees to old attacks.

The estimate of faders and volume loss by ownership class was made by multiplying the percent of acres falling in each ownership times the estimated faders and volume for each strata. The same procedure was used to obtain county level data. The sample design provided a statistical measure of precision at the state level. Estimates at the county/ownership does not have statistical properties.

Additional new attack (1979 infested) information taken from each ground plot was used to determine the ratio of old to new attacks for each strata. An example and formulae appear in Appendix B.

RESULTS

The estimated number of faders was 327,443 trees from 350,279 infested acres. Associated volume loss amounted to over 5.1 million cubic feet (Table 2).

TABLE 2. Estimates of numbers and volume of ponderosa pine faders (1978 MPB attacks) in the Colorado Front Range survey area of 1979.

Strata	Acres	Estimated No. Faders (Trees)	Standard Error (Trees)	Volume Lost (MCF)	Standard Error (MCF)	Volume Per Tree (CF)
Contiguous	320,229	291,979	48,415 (16.6)*	4,674	1,472 (31.5)*	16.0
Small and Scattered	30,050	35,464	7,723 (21.8)*	427	99 (25.2)*	12.0
TOTAL	350,279	327,443	49,027 (15.0)*	5,101	1,475 (28.9)*	15.6

* Relative Standard Error

Relative sampling errors were 15 and 28.9 percent for the faders and volume respectively. These relative sampling errors seem acceptable for management purposes. The 95% confidence intervals indicate that 19 out of 20 times the number of faders would fall between 278,416 and 376,470 and the fader volume between 3.6 and 6.6 million cubic feet.

Volume loss and the estimate of faders is prorated by percentage acres to ownership and county within each strata. These prorated data are displayed in Table 3 and have no statistical properties.

Linear regression analysis of faders determined from ground counts and from photo counts correlate (R^2) at 0.608 for the small and scattered strata and at 0.697 for the contiguous strata (Table 4).

TABLE 3. STATUS OF PONDEROSA PINE MORTALITY CAUSED BY MOUNTAIN PINE BEETLE IN COLORADO, 1979, PRORATED BY LAND OWNERSHIP CLASS FOR EACH STRATUM.

County	Land Ownership Class	Contiguous Stratum					Small and Scattered Stratum				
		Acres infested	No. of 1979 faders	Mortality of 1979 faders (MCF)	Standing dead (MCF)	Down dead (MCF)	Acres infested	No. of 1979 faders	Mortality of 1979 faders (MCF)	Standing dead (MCF)	Down dead (MCF)
Boulder	National Forest (Roosevelt)	32,881	29,980	47,992	128,401	28,175	115	136	163	303	1,085
	Other Federal	2,233	2,036	3,259	8,720	1,913	10	12	14	26	94
	State	506	462	739	1,976	434					
	Other Public										
	Private	33,790	30,809	419	131,951	28,954	113	133	161	297	1,066
	Total	69,410	63,287	101,309	271,048	59,476	238	281	338	626	2,245
Chaffee	National Forest (San Isabel)	3,583	3,267	5,230	13,992	3,070	255	301	362	671	2,405
	Other Federal	470	428	686	1,835	403					
	State	669	610	976	2,612	573					
	Other Public										
	Private	816	744	1,141	3,186	699	127	150	180	334	1,198
	Total	5,538	5,049	8,083	21,625	4,745	382	451	542	1,006	3,603
Clear Creek	National Forest (Arapaho)						197	233	280	519	1,858
	Other Federal	57	52	83	223	49					
	State	95	86	139	371	81					
	Other Public										
	Private	1,252	1,142	1,827	4,889	1,073	147	173	209	387	1,386
	Total	1,404	1,280	2,049	5,483	1,203	344	406	489	906	3,244
Custer	National Forest (San Isabel)	11,892	10,843	17,357	46,438	10,190	376	444	534	990	3,546
	Other Federal	274	250	400	1,070	235	72	85	102	190	679
	State	467	426	682	1,824	400	7	8	10	18	66
	Other Public										
	Private	12,962	11,818	18,919	50,617	11,107	1,075	1,269	1,528	2,830	10,138
	Total	25,595	23,337	37,358	99,949	21,932	1,530	1,805	2,174	4,028	14,429
Douglas	National Forest (Pike)	28,274	25,780	41,268	110,410	24,228	232	274	330	611	2,188
	Other Federal	141	128	206	551	121					
	State						7	8	10	18	66
	Other Public										
	Private	8,360	7,622	12,202	32,646	7,164	3,070	3,623	4,362	8,081	28,953
	Total	36,775	33,530	53,676	143,607	31,513	3,309	3,905	4,702	8,710	31,207
Elbert	National Forest										
	Other Federal										
	State										
	Other Public						134	158	190	353	1,264
	Private										
	Total						3,071	3,624	4,364	8,084	28,962
							3,205	3,782	4,554	8,437	30,226
El Paso	National Forest (Pike)	2,485	2,265	3,627	9,704	2,129	125	148	178	329	1,179
	Other Federal										
	State										
	Other Public										
	Private	2,790	2,544	4,072	10,895	2,391	3,869	4,566	5,498	10,184	36,488
	Total	5,275	4,809	7,699	20,599	4,520	3,994	4,714	5,676	10,613	37,667
Fremont	National Forest (San Isabel)	7,158	6,527	10,448	27,952	6,134	416	491	591	1,095	3,923
	Other Federal	1,042	950	1,521	4,069	893	1,452	1,714	2,063	3,822	13,694
	State	87	79	127	340	75	382	451	543	1,006	3,603
	Other Public										
	Private	224	204	327	875	192	2,167	2,557	3,079	5,704	20,437
	Total	8,511	7,760	12,423	33,236	7,294	4,417	5,213	6,276	11,627	41,657
Gilpin	National Forest (Arapaho)	133	121	194	519	114	22	26	31	58	207
	Other Federal										
	State						40	47	57	105	377
	Other Public										
	Private	25	23	36	98	21	227	268	323	598	2,141
	Total	158	144	230	617	135	289	341	411	761	2,725
Huerfano	National Forest (San Isabel)	101	92	147	394	87	792	935	1,125	2,085	7,469
	Other Federal						284	335	404	748	2,678
	State						14	16	20	37	132
	Other Public										
	Private	359	328	524	1,402	308	1,098	1,296	1,560	2,890	10,355
	Total	460	420	671	1,796	395	2,188	2,582	3,109	5,760	20,634
Jefferson	National Forest (Pike)	20,283	18,494	29,605	79,205	17,380	238	281	338	626	2,245
	Other Federal	132	120	193	515	113					
	State	281	256	410	1,097	241	52	61	74	137	490
	Other Public	3,100	2,827	4,525	12,106	2,656					
	Private	26,789	24,426	39,101	104,612	22,955	1,957	2,310	2,781	5,151	18,456
	Total	50,585	46,123	73,833	197,535	43,345	2,247	2,652	3,193	5,914	21,191
Larimer	National Forest (Roosevelt)	30,256	27,586	44,161	118,150	25,926	2,179	2,572	3,096	5,736	20,550
	Other Federal	378	345	552	1,476	324					
	State	49	45	72	191	42	224	264	318	590	2,113
	Other Public										
	Private	19,263	17,564	28,116	75,222	16,506	2,964	3,498	4,212	7,802	27,953
	Total	49,946	45,540	72,900	195,039	42,798	5,367	6,334	7,626	14,128	50,616
Park	National Forest (Pike)	7,208	6,572	10,521	28,147	6,176	684	807	972	1,800	6,451
	Other Federal	52	47	76	203	45	79	93	112	208	745
	State	398	363	581	1,554	341	148	175	210	390	1,396
	Other Public										
	Private	8,262	7,533	12,059	32,263	7,080	445	525	632	1,171	4,197
	Total	15,920	14,515	23,237	62,167	13,642	1,356	1,600	1,926	3,569	12,789
Pueblo	National Forest (San Isabel)	26,636	24,286	38,877	104,014	22,824					
	Other Federal	352	321	514	1,375	302					
	State	977	891	1,426	3,815	837					
	Other Public										
	Private	22,174	20,218	32,365	86,590	19,001					
	Total	50,139	45,716	73,182	195,794	42,964					
Teller	National Forest (Pike)	418	381	610	1,632	358	544	642	773	1,432	5,130
	Other Federal										
	State						49	58	70	129	462
	Other Public										
	Private	95	87	139	371	81	591	697	840	1,556	5,574
	Total	513	468	749	2,003	439	1,184	1,397	1,683	3,117	11,166

TABLE 4. Linear Regression Comparing the Photo Plot (y) to the Ground Data (x) by Stata and Combined

Strata	Number of Plots	y = A + bx a	b	R^2	Standard Error
Contiguous	49	1.163	1.075	.697	39.86
Small and Scattered	20	-1.477	2.094	.608	12.75
COMBINED	69	3.261	1.070	.690	34.42

The volume estimate for accumulated dead (i.e. all MPB caused mortality prior to 1978-attacked trees) within the survey area is 16.1 million cubic feet. The standing dead volume is 13.3 million cubic feet with a relative sampling error of 36.8 percent (Table 5). The volume of down dead is 2.8 million cubic feet with a relative sampling error of 38.5 percent (Table 5).

TABLE 5. 1979 Colorado Front Range Mountain Pine Beetle Loss Survey - Volume Estimates of Dead Ponderosa Pine

	Standing Dead		Down Dead	
Strata	Volume (MCF)	Standard Error (MCF)	Volume (MCF)	Standard Error (MCF)
Contiguous	12,505	4,873	2,744	1,089
Small & Scattered	791	491	90	40
TOTAL	13,296 (36.8)*	4,898	2,834 (38.5)*	1,090

* Relative Sampling Error

Basal area for all variable plots, both strata (contiguous; small and scattered) were summarized. The basal area of all trees and of ponderosa pine (live and dead) were estimated from data gathered in the variable plots (Table 6). Basal area for all tree species, including the dead, was 71.1 ft^2, live ponderosa pine was 53.8 ft^2, and dead ponderosa was 18 ft^2. The associated errors were 67, 79 and 178 percent.

TABLE 6. Summary of basal area data, 1979 Colorado Front Range Mountain Pine Beetle Loss Survey

	Trees ≥ 5" dbh	Basal Area (ft^2)
COMBINED (all variable plots, both strata)	Ponderosa (live)	53.8 (79)*
	Ponderosa (dead)	18.0 (178)*
	All tree species	71.1 (67)*

* Relative Standard Error

The ratio of the number of MPB infested trees in 1979 to those infested in 1978 (i.e. infestation ratio) was estimated for each stratum and for the combined strata. These ratios are given in Table 7.

TABLE 7. 1979 Colorado Front Range Mountain Pine Beetle Loss Survey Infestation Ratio (i.e. 1979 to 1978)

Strata	No. of 1979 trees infested	No. of 1978 trees infested	Ratio	Range
Contiguous	232	1,508	.15	.13 - .17
Small and Scattered	289	362	.80	.68 - .93
Combined	521	1,870	.28	.26 - .32

DISCUSSION

The estimates of faders resulting from this multistage survey were acceptable for management needs at this time. The survey design and subsequent stratification was to provide an estimate of the number and volume of faders. Secondary objectives incorporated into this survey were to estimate volume of accumulated dead caused by MPB, basal area of live trees to dead (standing and down) and the ratio of new infested trees (1979) to previous infested trees (1978).

The basal area estimates have very high standard errors and so use of this information should be with caution. In future surveys the methods to measure basal area should be within tree stands and not by the set system of 5 variable plot clusters as was done in this survey.

The infestation ratio for both strata and combined indicate a decrease in tree killing by the mountain pine beetles in 1980. Loss due to 1979 mountain pine beetle attacks is estimated to be about 92,000 trees, assuming the ratio for the combined is valid at 0.28.

In the early stages of planning this Front Range Colorado Mountain Pine Beetle Loss Survey, it was envisioned that tree loss information by county would be highly desirable. It was soon apparent that cost of tree loss data with statistical reliability would preclude attainment of such information. In lieu, it was decided to design the survey to attain acceptable statistically reliable loss estimates for appropriate stratum of the MPB infestation after completion of sketch mapping. The stratum established and sampled separately were: (1) contiguous, and (2) small and scattered, with their estimates (Table 2), which are statistically adequate.

Estimates of faders, resultant volume (MCF), volume (MCF) of dead ponderosa (standing and down by county) and strata are shown in Table 3. The afore mentioned are derived on the basis of infestation acres expanded by the mean per acre for each. There is no reliable statistical measure and should be used with extreme caution. At best this information provides an overview by county and for each national forest. The infestation acreages by county should be adequate for general project considerations but volumes of faders and dead is not likely to be adequate for project planning purposes.

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APPENDIX A

Formulae used for estimating strata level totals

1. Contiguous strata - primary sampling unit (PSU) is the 90 acre photo plot selected systematically from the contiguous strata

Notation

Subscripts:

$i = 1, \cdots, m$ denotes the sampled 90-acre photo plots

$j = 1, \cdots, n$ denotes the 90-acre photo plots selected for ground sampling

$k = 1, 2$ denotes the 2.5-acre subplots selected for each 90-acre photo plot

A : Number of acres

M : Number of primary sample units

$$M = \frac{A}{(90 \text{ acres})}$$

m : Number of photo plots sampled

n : Number of photo plots selected for ground sampling

x_i : Number of faders counted in the ith photo plot

x : Total number of faders counted

$$x = \sum_{i=1}^{m} x_i$$

x_{jk} : Number of faders counted from the photo in the kth subplot of the jth photo plot

y_{jk} : Number of faders counted on the ground, in the kth subplot of the jth photo plot

$\hat{y}_j$: Estimate of the number of faders in the jth photo plot

$\hat{Y}$: Estimate of the number of faders

S.E.$\hat{y}$: Standard error of the estimate

Estimators

$$\hat{Y} = \left[\frac{A}{(90)(m)(n)}\right] \sum_{j=1}^{n} \hat{y}_j$$

where

$$\hat{y}_j = \frac{x \left[\sum_{k=1}^{2} \frac{(x_j)(y_{jk})}{x_{jk}}\right]}{(x_j)(2)}$$

$$S.E._{\hat{Y}} = \sqrt{\left[\frac{A}{(90)(m)}\right]^2 \left[\frac{\sum_{j=1}^{n} \left(\hat{y}_j - \hat{Y}\right)^2}{n\,(n-1)}\right]}$$

Since $\hat{Y}$ is the mean of the $\hat{y}_j$ values, the above formula can be reduced to the following more easily calculated form:

$$S.E._{\hat{Y}} = \sqrt{\left[\frac{A}{(90)(m)}\right]^2 \left[\frac{\sum_{j=1}^{n} \hat{y}_j - \frac{\left(\sum_{j=1}^{n} \hat{y}_j\right)^2}{n}}{n\,(n-1)}\right]}$$

2. Small and scattered strata - the primary sampling unit (PSU) was the individual polygon selected PPS based on an estimated number of faders.

Notation

M : Number of primary sampling units - number of small and scattered polygons

Q_i : Number of estimated faders in the i^{th} polygon

Q : Total faders, $Q = \sum_{i=1}^{m} Q_i$

m : Number of polygons selected for photo sample

C_i : Number of faders counted in the i^{th} polygon/plot

R_i : Ratio of photo counts to sketch map count $R_i = C_i/Q_i$

C_{ij} : Number of faders counted in the i^{th} photo plot in the j^{th} sub-cell (2.5 acre)

X_{ij} : Number of faders counted on the ground in the j^{th} sub-cell

n : Number of polygons selected for ground sample

Estimators

$$\hat{Y} = \left\{ \sum_{k=1}^{20} \left[\frac{1}{m} \frac{\sum_{i=1}^{M} Q_i}{Q_i} \right] \cdot \left[\frac{\sum_{i=1}^{m} C_i/Q_i}{C_i/Q_i} \right] \cdot \left[\frac{C_i}{C_{ij}} \right] \cdot X_{ij} \right\} \frac{1}{n}$$

First Stage — Second Stage — Third Stage — Measurement Variable

For computational ease, the formula can be reduced:

let $Q = \sum_{i=1}^{m} Q_i$, $\quad R = \sum_{i=1}^{m} \frac{C_i}{Q_i}$ $\quad$ then $\quad \hat{Y} = \left[\frac{QR}{m} \right] \left[\sum_{k=1}^{n} \frac{X_{ij}}{C_{ij}} \right] /n$

The corresponding standard error (SE) is:

$$SE_{\hat{y}} = \sqrt{\frac{\left[\frac{1}{m} \cdot Q \cdot R \right]^2 \sum_{k=1}^{n} \frac{X_{ij}^2}{C_{ij}^2} - \frac{\sum_{k=1}^{n} \left[\frac{X_{ij}}{C_{ij}} \right]^2}{n}}{n(n-1)}}$$

APPENDIX B

Formulae used for estimating attack ratios

The population of interest consists of mountain pine beetle infested trees. The population consisted of two classes: total trees infected in 1978 (faders) and trees attacked in 1979 (new attacks). Ratios and confidence intervals for attack ratios are computed as follows:

A = Number of trees infested in 1979 counted in a given area

B = Number of trees infested in 1978 counted in a given area

N = A + B = Total of 1978 & 1979 infested trees counted in a given area

$P = \frac{A}{N}$ = proportion of total trees counted which were infested in 1979

$q = \frac{B}{N}$ = proportion of total trees counted which were infested in 1978

C.I. = Confidence Interval

90% C.I. for q is expressed as: $q \pm 1.96 \sqrt{\frac{pq}{N}}$

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